Airway Management and Smoke Inhalation Injury in the Burn Patient

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KEYWORDS

• Smoke inhalation injury • Burns • Burns inhalation
• Carbon monoxide poisoning • Hydrogen cyanide
• High-frequency ventilation

Plastic surgeons frequently provide care to patients who have burn injuries and concomitant smoke inhalation injury (II). About 10% of patients admitted to burn centers have II, which greatly increases their risk for postburn pneumonia and mortality, especially at the midranges of age and burn size.[1–3] This article reviews the essential diagnostic and therapeutic interventions in the treatment of these patients.

An understanding of II and what to do about it has only developed over the last 50 years. Consider the scene at Massachusetts General Hospital on the evening of November 28, 1942, following one of the largest indoor fire disasters in U.S. history, at the Cocoanut Grove nightclub. Of the approximately 1000 occupants, 114 were taken to Massachusetts General Hospital within 2 hours, of whom 39 lived to be admitted:

> *As the patients from the scene of the disaster were crowded into the hospital it became apparent early that they were divided sharply into two groups: the living and the dead or near dead. None in the former group died in the first 12 hours; none in the latter group lived more than a few minutes after arrival.*[4]

It is not entirely clear which process—carbon monoxide poisoning, hypoxia, upper-airway obstruction, or a combination—was responsible for these early deaths:

> *The first clue to the high incidence of pulmonary burns was afforded by the number who died within the first few minutes after reaching the hospital. They were cyanotic, comatose, or restless, and had severe upper respiratory damage…some were cherry-red in color, suggesting carbon monoxide inhalation.*[4]

Of those who were admitted, five developed progressive dyspnea and pulmonary edema over the next several hours that required "radical therapy" (ie, endotracheal intubation, immediate tracheostomy, and delivery of oxygen by tent or transtracheal catheter). In the "final stage" of the injury, they developed diffuse bronchiolitis, mucous plugging, peripheral airway obstruction, and lobular collapse. Uncharacteristically, pneumonia was not observed.[4]

Although it is incomplete from a current-day standpoint with respect to answers, the Cocoanut Grove monograph poses many of the same questions that burn specialists, faced with a patient who has severe II, must address today:

- What are the indications for endotracheal intubation?
- What is the ideal timing for tracheostomy?
- What diagnostic procedures should be performed for patients who are suspected of having II?
- Which method of gentle mechanical ventilation should be used for these patients?
- Are there any special fluid resuscitation requirements?
- Which drugs may improve outcome?

The opinions or assertions contained herein are the private views of the author, and are not to be construed as official or as reflecting the views of the Department of the Army or Department of Defense.
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- How should carbon monoxide and hydrogen cyanide (HCN) poisoning in patients who have II be treated?
- Should patients who have II be transferred to a burn center?
- Are there any life-threatening, long-term sequelae of II?

The pathophysiology of II is complex, but it can be classified into three types, based on anatomic location. The first type includes upper-airway injuries caused primarily by thermal injury to the mouth, oropharynx, and larynx. The second type includes lower airway and parenchymal injuries (eg, tracheal, bronchial, and alveolar injuries) caused by chemical and particulate constituents of smoke. Unless otherwise specified, the term ''inhalation injury'' usually means injuries of this type. The third type includes metabolic asphyxiation, which is the process by which certain smoke constituents (most commonly carbon monoxide or HCN) impair oxygen delivery to, or consumption by, the tissues. All three types of II may coexist in a given patient, whose care may be further complicated by cutaneous burns or mechanical trauma.

AIRWAY MANAGEMENT

The indications for endotracheal intubation in patients who have II include decreased mental status resulting from inhalation of metabolic asphyxiants (see the later discussion in this article) or from other injuries, airway obstruction caused by II or generalized postburn edema, and pulmonary failure resulting from subglottic II. Direct thermal injury to the upper airway (including the larynx, oropharynx, mouth, and tongue) causes edema formation, which may progress to complete airway obstruction within minutes or hours. Orotracheal intubation of such patients after the onset of obstruction is often impossible (**Fig. 1**A), and immediate cricothyroidotomy should then be considered. To avoid that scenario, prophylactic intubation is appropriate.

Patients who have postburn facial and airway edema and those who have symptomatic inhalation injury should be recognized as having potentially difficult airways, and a highly experienced provider should perform the intubation. As with any difficult airway, paralytic agents should be used with caution lest they lead to a ''can't intubate, can't ventilate'' scenario. Instead, the use of short-acting drugs such as fentanyl, midazolam, or propofol may be preferable. Premedication for direct laryngoscopic examination should be performed with an appreciation for the fact that many patients who have II are hypovolemic and may become profoundly hypotensive upon induction of anesthesia. Thus, the author frequently uses intravenous ketamine in doses

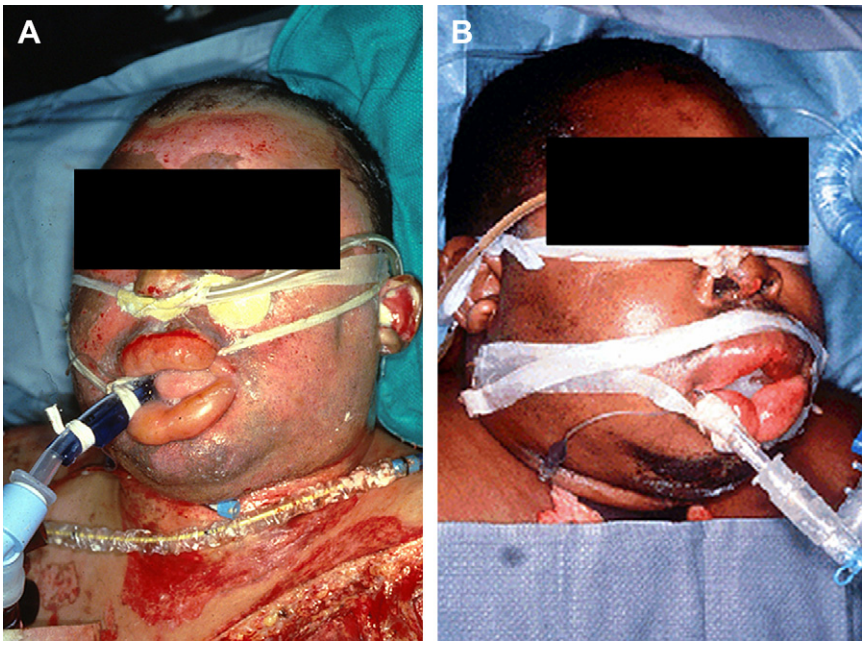

Fig. 1. (*A*) The endotracheal tube must be circumferentially secured around the head and neck of the patient who has significant thermal injury or inhalation injury, using cotton ties or similar methods. Note that care must be taken to protect the corner of the mouth, if possible. (*B*) Adhesive tape will not stick to a burned face.

one quarter to one half of the full anesthetic dose for this purpose (ie, 0.25–0.5 mg/kg, instead of 1 mg/kg). In a patient who is awake and in situations that are not true emergencies, intubation using a transnasally inserted fiberoptic bronchoscope with topical anesthesia is another excellent approach. The primary risk associated with prophylactic intubation in such patients is catastrophic loss of the airway, especially during transport. Thus, cotton ties (1/2-in umbilical ties), rather than adhesive tape, are used to secure the endotracheal tube circumferentially around the patient's neck (see **Fig. 1**A, B). Also, the tube may become obstructed in patients who have copious mucous production. This may be prevented by frequent (hourly or more often) suctioning (**Fig. 2**A, B).

Although II directly damages the airway, cutaneous thermal injury causes generalized edema throughout the body, including the airway. Some children who have scald injuries and no II whatsoever require endotracheal intubation, in particular when they are younger than 2.8 years old and the burns cover more than 19% of the total body surface area (TBSA).[5] In adults, the author recommends prophylactic endotracheal intubation for patients who have burns over more than 40% of the TBSA until the resuscitation period is complete (first 48 hours), even when II is absent.

Not all patients who have smoke exposure require endotracheal intubation.[6] Awake transnasal fiberoptic laryngoscopic examination can be used to determine whether a patient who has mild symptoms also has laryngeal edema and requires intubation.[7,8] The author uses a bronchoscope for this purpose because it permits evaluation of the subglottic airway (see the later discussion in this article).

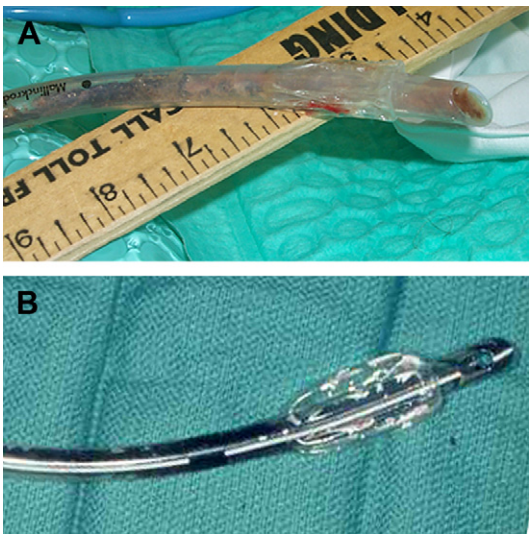

Fig. 2. (*A*) Endotracheal tube completely blocked by inspissated mucus and debris. (*B*) Endotracheal tube completely blocked by mucus and carbonaceous sputum. In both cases, emergency extubation and reintubation were required.

As with patients who are mechanically ventilated for other reasons, every effort should be made to liberate the patient who has II from the ventilator as soon as possible. To this end, the author performs daily sedation breaks and reevaluations for extubation. He also uses aggressive physical therapy, including tilt-table exercises, standing, and even ambulation, in selected patients despite the presence of an endotracheal or tracheostomy tube. Contraindications to extubation, aside from those common to all patients, include upper-airway edema so severe that the patient cannot breathe around an occluded endotracheal tube with the cuff deflated, worsening edema (due to resuscitation during the first 48 hours postburn), and significant problems with pulmonary toilet. Note that the airways do not have to be completely healed because natural coughing is effective at clearing moderate amounts of plugs, secretions, and other matter.

Whether and when to perform tracheostomy for patients who have II continues to be debated. In both adults and children, the route of intubation seems less important than avoidance of high peak inspiratory pressures and high cuff pressures.[9–11] The author's practice is to perform tracheostomy at 14 days for those patients who remain ventilator dependent.

Earlier tracheostomy may be necessary to facilitate pulmonary toilet, which may be lifesaving in patients who have severe II when they begin to slough the airway mucosa, bleed into the airway, and form obstructing clots and casts. This may begin within a few days after the injury (**Fig. 3**A, B). Performing a percutaneous tracheostomy may be more challenging in patients who are bleeding into the airway, and an open tracheostomy may be advantageous in that setting.

DIAGNOSIS OF INHALATION INJURY

Before transferring a patient to a burn center, it is sufficient to identify the patient's risk for airway and breathing problems and to protect the airway, and it is not usually necessary to make a definitive diagnosis as to the presence or absence of II. For this purpose, fiberoptic laryngoscopic examination (see the previous discussion in this article), patient history and physical examination, and carboxyhemoglobin levels (if available) are used. The mechanism of injury, signs, symptoms,

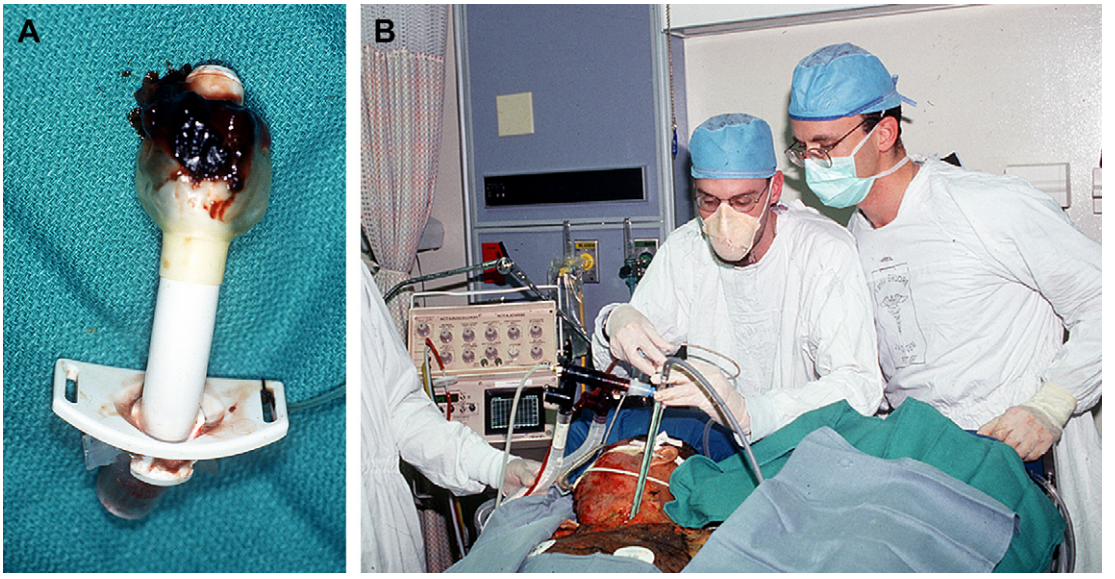

Fig. 3. (*A*) Tracheostomy tube blocked by coagulated blood in a patient who had severe II. (*B*) The patient required removal of the tracheostomy tube, rigid bronchoscopy performed through the stoma and high-frequency ventilation performed through the side port, and removal of obstructing tracheal-bronchial clots performed using direct visualization. The use of inhaled heparin may help prevent such problems.

and physical examination provide clues to the presence of II, but not diagnostic certainty. Shirani and colleagues[1] found that patients who have a history of injury in a closed space, facial burns, large burn sizes, or advanced age are more likely to have II. Other clues to diagnosis include the patient's loss of consciousness at the fire scene and the presence of noxious fumes at the fire. Clark and colleagues[12] retrospectively reviewed the presenting symptoms of 805 patients who had II. In 108, complete data were available (**Table 1**). From these data, it can be deduced that the absence of classic signs of airway obstruction (eg, stridor, voice change, dyspnea) should not reassure one that II is absent.

Fiberoptic bronchoscopy (FOB) provides what has been called a "gold standard" for the diagnosis of II.[13] Several authors have developed grading schemes for the severity of injury based on data from FOB.[14–16] One such system was prospectively evaluated and is provided in **Table 2**. In addition, patients may have varying amounts of carbonaceous material (soot) in the airways, may have copious or no secretions, may progress from necrosis to sloughing of the airway, and may present with areas of pallor rather than hyperemia (**Fig. 4**A, B). Finally, FOB may be falsely negative if an FOB examination is performed immediately after injury in patients who have burn shock. A repeat FOB examination 24 to 48 hours later may be more revealing.[17] Efforts to grade the severity of II by the macroscopic appearance of the airways using FOB examination have been inconsistent and subjective. When the diagnosis is uncertain by FOB, biopsy may be helpful but is not widely used.[18,19]

Most patients who have II have a normal chest radiograph on initial presentation. Thus, a normal chest radiograph cannot be used to rule out

Table 1
Frequency of physical examination findings in patients who had inhalation injury

Findings	Frequency (%)
Burns, face	65
Carbonaceous sputum	48
Soot, nose and mouth	44
Wheeze	31
Rales, rhonchi	23
Voice change	19
Corneal burn	19
Singed nasal vibrissae	11
Cough	9
Stridor	5
Dyspnea	3
Intraoral burn	2

Adapted from Clark WR, Bonaventura M, Myers W. Smoke inhalation and airway management at a regional burn unit: 1974–1983. Part I: Diagnosis and consequences of smoke inhalation. J Burn Care Rehabil 1989;10:52–62.

Table 2
Grading scheme for fiberoptic bronchoscopy findings in inhalation injury

Grade	Findings	Mortality (%)
0	Normal (no II)	0
B	Positive based on biopsy only	0
1	Hyperemia	2
2	Severe edema and hyperemia	15
3	Severe injury: ulcerations and necrosis	62

Adapted from Chou SH, Lin SD, Chuang HY, et al. Fiber-optic bronchoscopic classification of inhalation injury: prediction of acute lung injury. Surg Endosc 2004;18:1377–79.

II.[12,20–23] Later changes, including bronchial thickening, perivascular fuzziness or cuffing, alveolar or intersititial pulmonary edema, consolidation, and atelectasis, have been reported.[20–23]

In sheep, Park and colleagues[24] described the CT findings associated with II. Scoring the severity of CT findings (eg, normal, interstitial markings, ground-glass, or consolidation) allowed differentiation of the sheep according to severity of the smoke dose (eg, control, mild, moderate, severe) at 24 hours after contracting II. A human trial has not been performed. ''Virtual bronchoscopy'' using three-dimensional CT scan reconstructions of the upper airway permitted one group of investigators to diagnose edema of the epiglottis and glottis.[25] A similar approach to imaging the lower airways has not been described.

Xenon^{133} is a radioactive tracer that is injected intravenously and exhaled from the lungs. Using xenon^{133} permits visualization of an injury process beyond the reach of FOB examination (ie, at the level of the small airways). Failure to clear the xenon^{133} in 90 seconds (in one paper, 150 seconds) or segmental retention of the xenon^{133} is diagnostic of II.[17,26–28] The presence of asthma, chronic obstructive pulmonary disease, and blebs may cause false-positive results. Agee and colleagues[27] determined the accuracy of xenon^{133} scanning to be 86%. In Shirani and colleagues'[1] large series, those patients who had positive xenon^{133} scans but negative results on FOB examination had a lower risk for pneumonia and for mortality, which indicated a milder form of II. Aerosolized technetium 99-m that is complexed to diethylenetriaminepentacetate (Tc99m-DPTA) diffuses across the alveolar-capillary membrane into the blood. The presence of II delays the absorption, and thus the disappearance, of this tracer. In dogs, this technique was more sensitive than xenon^{133} scanning in the immediate postburn period (within minutes). Human data are

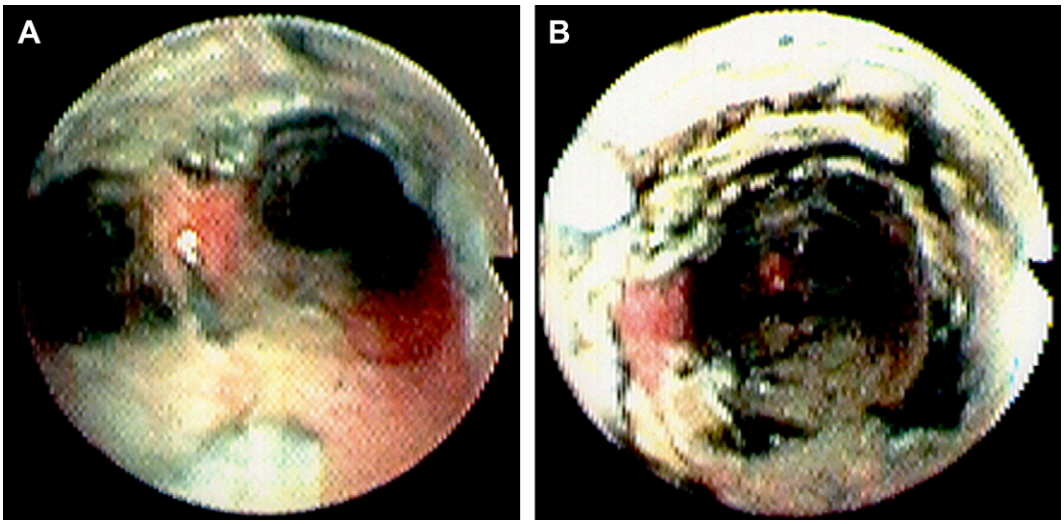

Fig. 4. (*A*, *B*) Typical appearance of the carina during fiberoptic bronchoscopic examination of patients who have severe II.

limited.[29,30] These methods require transport to a nuclear medicine suite, and thus are mainly used as research tools.

For patients who do not require intubation, pulmonary function testing may be used to screen patients for II.[31] II causes decreases in peak flow and increased pulmonary resistance.[32] Pulmonary function tests are also useful for long-term follow-up of such patients to detect those with subglottic stenosis and similar conditions (see the later section in the article).

MECHANICAL VENTILATION

The best mode of mechanical ventilation for patients who have II has not been determined. Although the Lower Tidal Volume Trial (ARMA) conducted by the ARDS Network showed that lower tidal volumes (eg, 6 mL/kg) are associated with improved survival in patients who have acute respiratory distress syndrome (ARDS), the study excluded patients who had burns in excess of 30% of their TBSA.[33] There is reason to believe that the ARMA results may not be fully applicable to patients who have II. The author believes that II is fundamentally different from other types of ARDS.[34] The principal cause of hypoxemia in patients who have ARDS induced by pulmonary contusion, systemic injury, or sepsis is alveolar flooding and an increase in true shunt. In patients who have II, chemical damage to the small airways predominates and causes an increase in a ventilation-perfusion mismatch that is manifested by an increase in blood flow to poorly ventilated lung segments.[35] As small airways obstruction progresses, atelectasis followed by consolidation and pneumonia ensue. Thus, treatment of patients who have II, in contrast to those who have other forms of ARDS, must focus not only on avoiding ventilator-induced lung injury but also on actively providing pulmonary toilet and recruiting and stabilizing collapsed alveoli.

This belief is the rationale for the use of high-frequency percussive ventilation by means of a Volumetric Diffusive Respiration ventilator (VDR-4, Percussionaire, Sandpoint, Idaho). The VDR-4 is different from high-frequency jet or oscillation ventilators. It combines both subtidal, high-frequency (eg, 400–1000 breaths/min) and tidal, low-frequency (eg, 0–20 breaths/min) ventilation (**Fig. 5**A, B). With the VDR-4, gas exchange at lower peak and mean airway pressures occurs as a result of a variety of mechanisms, including more turbulent flow and enhanced molecular diffusion.[36,37] Unique to the VDR-4, the high-frequency, flow-interrupted breaths effect dislodgement of debris and cause its retrograde expulsion out of the airways. For this reason, the author partially deflates the endotracheal tube cuff (to a minimal leak level) and frequently suctions the oropharynx because plugs and secretions in patients who have II can be copious. Finally, the VDR-4, like airway-pressure release ventilation (also known as bilevel ventilation), enables spontaneous ventilation throughout the inspiratory and expiratory phases. In most cases, this improves patient-ventilator synchrony, and as with airway-pressure release ventilation, may have other beneficial effects on gas distribution and respiratory muscle strength.

To date, clinical trials of the VDR-4 have been retrospective or have not been adequately powered to detect an improvement in mortality.[37] Cioffi and colleagues[38] described 54 patients who had II and who were treated using VDR-4 during the period from 1987 to 1990, and they compared observed mortality and pneumonia rates to those predicted by data from the recent past, in which conventional ventilation was used (12–15 mL/kg tidal volumes). The VDR-4 was associated with a reduction in mortality from 43% (predicted) to 19% (observed), and with a reduction in pneumonia from 46% (predicted) to 26% (observed). That paper led to the authors adopting the VDR-4 for treatment of patients who had II at the U.S. Army Burn Center.

Hall and colleagues[39] compared 92 patients who had II and who were treated using the VDR-4 with 130 well-matched concurrent patients who had II and who were treated using conventional ventilation. The VDR-4 was associated with a significant decrease in mortality in those patients who had burns that covered less than 40% of the TBSA. Other investigators have documented improved gas exchange at lower airway pressures when using the VDR-4.[40–42] Currently, the U.S. Army Burn Center is conducting a prospective, randomized trial of the VDR-4 compared with low-tidal volume conventional ventilation in patients who have burns and who require mechanical ventilation.

Patients who have circumferential, deep burns of the chest often develop respiratory compromise, whether or not II is present. The cause of this thoracic eschar syndrome is progressive edema formation beneath the tight, inelastic skin, which generates a straightjacket-like impediment to respiratory excursion. Decreased compliance during bag ventilation, increasing peak airway pressures when on the ventilator, and rising end-tidal carbon dioxide ($ETCO_2$) and partial arterial pressure of carbon dioxide ($PaCO_2$) levels presage a rapidly lethal phenomenon. After quickly ruling out an airway

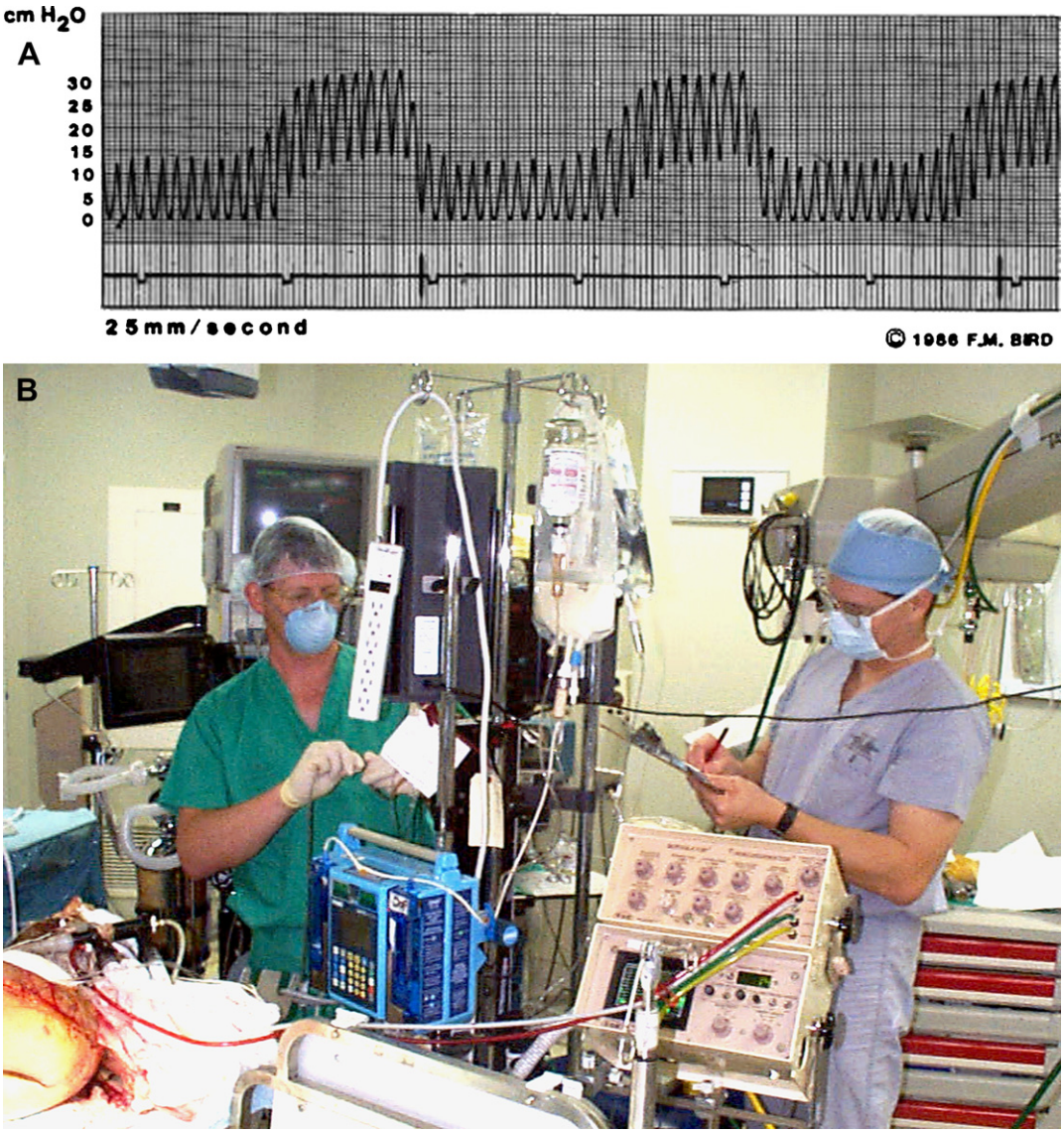

Fig. 5. (*A*) High-frequency percussive ventilation: pressure-time waveform for the VDR-4 volumetric diffusive respiration ventilator. High-frequency subtidal breaths are combined with low-frequency tidal breaths. The percussive action of the high-frequency breaths improves gas exchange, recruits collapsed alveoli, and effects pulmonary toilet. (*Adapted from* Percussionaire, Inc) (*B*) Continuation of high-frequency percussive ventilation in the burn operating room using total intravenous anesthesia avoids derecruitment and alveolar collapse.

problem (eg, kinked, dislodged, or obstructed endotracheal tube) or tension pneumothorax, the treatment for this syndrome is rapid bedside thoracic escharotomy (**Fig. 6**). Others causes of impaired ventilation in such patients include severe bronchoconstriction, which usually responds to inhaled albuterol and rarely requires the use of inhaled corticosteroids, and abdominal compartment syndrome, which is seen in patients who receive excessive amounts of fluid (eg, 250 mL/kg) during the first 24 hours postburn.

FLUID AND PHARMACOLOGIC THERAPY

Fluid resuscitation of patients who have II is likely to be difficult. Patients who have *isolated* II rarely have prodigious fluid resuscitation requirements. It is well known, however, that the addition of II in patients who have cutaneous burns greatly increases the fluid resuscitation requirements during the first 48 hours postburn.[43] In one study, patients who were resuscitated using the modified Brooke formula (which advises the use of

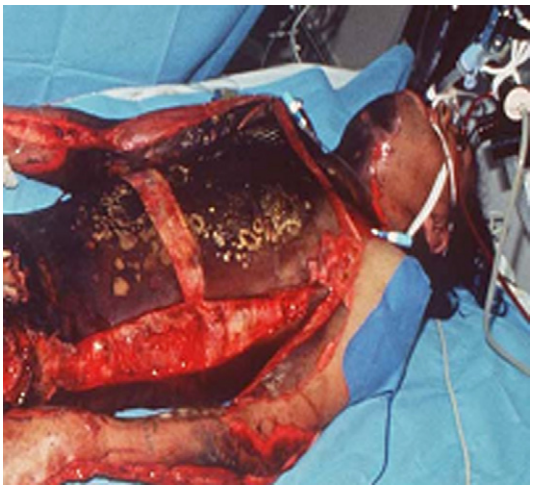

Fig. 6. Patient with deep circumferential burns of the chest and abdomen that impaired chest excursion, causing thoracic eschar syndrome. Emergency chest escharotomies were performed at the bedside using a scalpel, which restored normal compliance and effective mechanical ventilation.

2 mL/kg/TBSA burned as the lactated Ringer's dose for the first 24 hours) actually received more than 5 mL/kg/TBSA burned.[44] Efforts to anticipate this response by starting patients on higher infusion rates are likely to result in increased complications of volume overload.[45] On the other hand, fluid restriction does not protect the lungs or improve outcome. For example, Herndon and colleagues[46] demonstrated an increase in lung lymph flow (indicating increased microvascular permeability) in fluid-restricted sheep with combined II and burns. Thus, resuscitation of patients who have combined II and burns should be conducted with close attention to providing neither too much nor too little fluid, with hourly attention to endpoints such as achieving urine output of 30 to 50 mL/h in adults or 1 to 1.5 mL/kg/h in children who weigh less than 30 kg.

Despite research that has greatly improved the understanding of the pathophysiology of inhalation injury,[47] pharmacologic options for treatment of II remain limited. Nevertheless, inhaled heparin is an important addition. In a retrospective study, Desai and colleagues[48] reported a reduction in re-intubation rates and mortality in burned children who were treated using inhaled heparin and *N*-acetylcystine. On the other hand, Holt and colleagues[49] reviewed their experience with the use of inhaled heparin and *N*-acetylcystine in adults who had II. There was no difference in the number of days on a ventilator or in mortality between those who received this treatment and those who did not. The divergent results of the two studies may be due to the fact that children, who have smaller airways and endotracheal tubes, are more vulnerable to airway obstruction.[5] Because obstructing clots and casts are a common life-threatening problem during the acute phase for people who have II, and because this therapy is inexpensive and does not cause systemic anticoagulation, the author routinely provides nebulized heparin to all patients who have II, beginning on admission and continuing as long as the patients are intubated and their airways remain friable.

Pneumonia, most often secondary to invasive gram-negative rods (such as *Pseudomonas aeruginosa* or *Klebsiella pneumoniae*) or to *Staphylococcus aureus*, remains a dreaded complication in patients who have II or extensive thermal injury.[1,50,51] Unfortunately, prophylactic antibiotics have not been shown to prevent infection in patients who have II or burns. Especially when hospitalized for weeks to months, such patients are at risk for colonization and infection with multiple drug-resistant organisms; this risk increases with indiscriminant antibiotic exposure. Compounding the problem is the fact that burn injury alone causes hyperdynamic systemic inflammatory response syndrome, which is characterized by many of the same signs and symptoms as sepsis. Thus, elevated temperature or white blood cell count do not correlate well with systemic infection,[52] so other clinical indicators (eg, hyperglycemia, tachypnea, tube-feeding intolerance) must be sought. Early institution of broad-spectrum antibiotics, an aggressive diagnostic approach that includes bronchoalveolar lavage, and rapid tailoring of the regimen to match organism sensitivities are crucial.

METABOLIC ASPHYXIANTS

Along with smoke, patients can inhale compounds that impair oxygen delivery to, or use by, the tissues. Chief among these is carbon monoxide, which is produced by the partial combustion of carbon-containing compounds such as cellulosics (eg, wood, paper, coal, charcoal), natural gases (eg, methane, butane, propane), and petroleum products. Carbon monoxide poisoning is a common cause of death at fire scenes[53,54] and is also a leading cause of non–fire-related deaths in the United States.[55] In addition to combining with hemoglobin to form carboxyhemoglobin (COHb), where in the CO has an affinity for hemoglobin which is 200 times that of oxygen, carbon monoxide also impairs mitochondrial function and COHb causes brain injury as the result of oxidative stress, inflammation, and excitatory

amino acids.[56] The organs most vulnerable to carbon monoxide poisoning are those most affected by oxygen deprivation, namely, the cardiovascular system and the brain.

Currently, the diagnosis of carbon monoxide poisoning requires measurement of arterial COHb levels using a co-oximeter; the PaO_2 level in such patients is frequently normal or high, and a standard 2-wavelength pulse oximeter will falsely provide a high peripheral saturation of oxygen (SpO_2) reading, even when COHb levels are in the lethal range ($\geq$50%), because it cannot discriminate between COHb and oxygenated hemoglobin.[57] Only an arterial saturation of oxygen (SaO_2) reading derived from an arterial blood gas sample and analyzed using a co-oximeter will show depressed hemoglobin oxygen saturation. The half-life of COHb may be variable; in one study, the half-life of COHb in patients treated using 100% oxygen was 74 min $\pm$ 25 SD, but ranged from 26 to 148 minutes.[58]

The mainstay of treatment is 100% oxygen administered by nonrebreather mask or endotracheal tube until the COHb level is less than 5%[59] or for 6 hours.[60] Controversy surrounds the use of hyperbaric oxygen therapy (HBOT) to treat such patients. Although HBOT accelerates the clearance of carbon monoxide beyond that achieved using 100% oxygen at 1 atmosphere, the main rationale for its use is prevention of delayed neurocognitive syndrome. This syndrome produces memory loss and other cognitive defects, with onset from 2 to 28 days after exposure.[60,61] The Cochrane group reviewed 6 randomized controlled trials (RCTs) of HBOT for prevention of neurologic sequelae. Four studies showed no benefit, two studies did show benefit, and the pooled analysis showed no benefit. The investigators concluded that the efficacy of HBOT in this setting is uncertain.[62] In the special case of a patient who has burns, II, and carbon monoxide poisoning, there is almost no evidence concerning the use of HBOT. Grube and colleagues[63] described a case series of 10 such patients who were treated using HBOT. Several significant problems complicated the use of HBOT, including aspiration, seizures, and progressive hypovolemia. That experience pointed to the difficulty inherent in transporting hemodynamically unstable patients who have burn shock and II to an HBOT chamber and providing care in the chamber. Furthermore, the data suggest that the use of HBOT for prevention of delayed neurocognitive syndrome need not begin until the twenty-third hour after exposure. The author does not routinely provide HBOT to patients during resuscitation from burn shock.

HCN is produced by the combustion of materials such as plastics, foam, paints, wool, and silk. It impairs the cellular use of oxygen by binding to the terminal cytochrome on the electron transport chain, causing lactic acidosis and, potentially, elevated mixed venous oxygen saturation. The half-life of HCN in the human body is about 1 hour. Thus, HCN may be a significant factor in a variable percentage of patients who have II.[53,64]

The diagnosis of HCN poisoning is difficult because a rapid assay is not available. HCN and carbon monoxide poisoning share many features, including signs and symptoms related to the central nervous and cardiovascular systems. A list of features that can be observed and compared is provided in **Table 3**. Three types of antidote are available for HCN poisoning. A HCN antidote kit in the United States contains amyl nitrite for inhalation and sodium nitrite and sodium thiosulfate for intravenous injection. The nitrites oxidize hemoglobin to methemoglobin, which

Table 3
Carbon monoxide and HCN poisoning comparison

Features	Carbon Monoxide	HCN
Loss of consciousness	May be transitory	Usually sustained
Dilated pupils	Rare	Common
Seizure	Uncommon	Common
Hypotension	Uncommon	Common (after initial "catecholamine rush")
Breathing	Tachypnea	Tachypnea, then bradypnea/central apnea
Lactate (correlation with levels of toxin)	Variable	Strong

Adapted from Baud FJ. Cyanide: critical issues in diagnosis and treatment. Hum Exp Toxicol 2007;26:191–201.

chelates HCN. Sodium thiosulfate combines with HCN to form thiocyanate, which is excreted in the urine. The author does not recommend the use of nitrites in patients who have II and suspected HCN poisoning. The nitrates can cause severe hypotension, and the methemoglobin does not transport oxygen,[65] which can be problematic, particularly in patients who have burn shock and impaired transport and use of oxygen resulting from the carbon monoxide and HCN poisoning. Certainly, nitrites should not be used in patients who have II without knowledge of their COHb and methemoglobin levels.[66] Sodium thiosulfate is a safer alternative, but the onset is slow.[67]

Recently, hydroxocobalamin (a form of vitamin B_{12}) has become available for intravenous injection in the United States, marketed using the brand name Cyanokit, (Dey, L.P., Napa, California). This drug is well tolerated and rapidly chelates HCN.[68] Now that a safe and effective antidote to HCN poisoning is available (and recognizing that most studies demonstrate HCN toxicity in a minority of patients who have II), the author believes it would be reasonable to administer intravenous hydroxocobalamin to patients who have II and who have signs and symptoms suggestive of HCN poisoning, such as persistent lactic acidosis, unexplained loss of consciousness, and others (**Box 1**).

BURN CENTER REFERRAL

The presence of II is one of the American Burn Association criteria for burn center referral.[69] Many of the modalities mentioned in this article are not routinely available outside of burn centers, including the expertise of respiratory therapists and other health care professionals who have the experience to provide optimal care to patients who have this highly lethal injury. Certainly, smoke-exposed patients who have an unremarkable physical examination, who show alert mental status, and who have normal blood gases and COHb levels may safely be discharged home.[70] For all those patients who have II and who require admission, the author recommends, at a minimum, prompt consultation with the regional burn center.

Box 1
Some long-term complications of smoke-inhalation injury

- Bronchiectasis[81–83]
- Bronchiolitis obliterans[83]
- Endobronchial polyposis[84,85]
- Main bronchial stenosis[73]
- Tracheal stenosis[73,77,86]
- Subglottic stenosis[73,77]
- Vocal cord paresis, fixation, fusion; arytenoid dislocation[33,87]
- Dysphonia (various causes)[74]

LONG-TERM COMPLICATIONS

Plastic surgeons who perform reconstructive surgery for patients who have burns may encounter those with long-term airway and pulmonary complications resulting from II (see **Box 1**). This is an area about which little has been published.[71] Regardless of the route chosen for airway control (and even in the absence of intubation), patients who have II are at risk for long-term glottic, subglottic, and tracheo-bronchial complications from the combination of injury, intubation, infection, and chronic inflammation.[72,73] These problems may arise after as few as 3 days of intubation;[6] the risk increases after about 21 days.[43]

Long-term follow-up, to include pulmonary function tests (eg, spirometry) and stroboscopic examination of the larynx, permits early detection and correction of these complications.[44,73,74] On pulmonary function testing at a 6-month follow-up examination, for example, survivors of a subway fire had persistent decreases in maximal expiratory flow rates, at 25% of vital capacity, which is consistent with continued abnormalities of the small airways.[75]

Analogous, perhaps, to the risk for hypertrophic scarring that is inherent when reconstruction is performed too soon after injury, chronic inflammation in the airway[76] may increase the risk for restenosis when post-II strictures are treated prematurely using surgical resection. T-tubes and stents may be useful in this setting.[73,77]

SUMMARY

II remains a important independent predictor of postburn death.[78] Attention to the principles highlighted in this article (eg, aggressive airway management, gentle mechanical ventilation, careful titration of fluid resuscitation, appropriate treatment of carbon monoxide and HCN poisoning, early diagnosis and treatment of pneumonia, early burn center referral, and long-term follow-up) has resulted in a significant reduction in mortality for patients who have II in the time since the 1942 Cocoanut Grove fire described in the introduction to this article.[79,80] The efforts of all the members of

the multidisciplinary burn team, including nurses, physicians, respiratory therapists, and basic scientists, among others, have contributed and will continue to contribute to progress for patients who have this difficult injury.

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